Human Serum Albumin Adsorption on Hydrogel Contact Lenses In Vitro

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Purpose. To improve the understanding of the formation of protein deposits on hydrogel lenses.

Methods. A study of protein adsorption on three commercial hydrogel contact lenses of different materials, Etafilcon A (2-hydroxyethyl methacrylate [HEMA] polymer with sodium methacrylate and 2-ethyl-2-hydroxymethyl-1,3-propanediol trimethacrylate), tefilcon (poly[HEMA] cross-linked and copolymerized with ethylene glycol dimethacrylate), and vifilcon A (methacrylic acid polymer with ethylene glycol dimethacrylate, HEMA and N-vinyl pyrrolidone) was undertaken by using a single protein solution, human serum albumin (HSA), and a radiolabel-tracer technique.

Results. Static adsorption leading to multilayer adsorption was observed. Complete reversibility for adsorbed HSA on lenses did not exist. Some was tightly bound, whereas most was loosely bound and could be removed easily by rinsing in phosphate-buffered saline. Irreversible adsorption of HSA on the lenses was found to be time dependent and did not reach a maximum value even after 48 hours of adsorption. The amount of HSA adsorbed on the lenses—irreversibly as well as totally adsorbed protein—was in the order of vifilcon A > tefilcon > etafilcon A. Adsorption of HSA on the lenses increases with decreasing pH (range, 7.4 to 4) but always follows the above trend with respect to the different types of lenses.

Conclusions. Irreversible binding of HSA on lenses is governed by the kinetics of protein denaturation. Electrostatic interactions may not play a major role in HSA adsorption on hydrogel lenses. Some other factors, such as hydrophobic dehydration, and special monomer units, such as *N*-vinyl pyrrolidone in the lens materials, may favor adsorption of HSA. Invest Ophthalmol Vis Sci. 1996;37:2594–2602.

Although poly(methyl methacrylate) (PMMA) has been used for many years as the standard hard contact lens material, its properties are far from ideal. It was not until hydrogel polymers (water-swollen networks based on hydrophilic monomers) appeared, however, that there was any major alternative caused by their increased oxygen permeability and ease of fit.[1] However, the most persistent problem in the application of hydrogel contact lenses during the past decade has been ocular incompatibility or spoilage that was not previously significant with PMMA lenses.[2] Spoilage of contact lenses usually is manifested by a deposit formation over the lens that interferes with vision and can be a source of ocular irritation, limiting the time that contact lenses can be worn before cleaning becomes necessary. Surface deposits are composed mainly of substances normally present in the tear film and are primarily proteins with lipids and carbohydrates in smaller amounts.[3–6] Although diverse tear components may contribute to contact lens coatings, proteins are of special interest because of their assumed potential for producing immunologic reactions.[7] Therefore, an understanding of the fundamental mechanisms involved in the interfacial interactions between proteins and contact lens polymeric materials would be of prime importance for the design of strategies for the development of deposition-resistant hydrogel contact lenses.

Early work with protein solutions on surfaces with

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TABLE 1. Hydrogel Contact Lenses and Lens Materials

Trade Name	*USAN Name*	*FDA Category (Group)*	*Water Content (%)*	*Principal Chemistry*
CIBASOFT	Tefilcon	1	38	HEMA, MA (trace)
New Vues	Vifilcon A	4	55	HEMA, PVP, MA
ACUVUE	Etafilcon A	4	58	HEMA, MA, NaMA random

USAN = U.S. Adopted Names; FDA = Food and Drug Administration; Group 1 = low water (<50%), nonionic; Group 4 = high water (>50%), ionic; HEMA = hydroxy ethyl methacrylate; MA = methacrylic acid; PVP = polyvinyl pyrrolidone; NaMA = sodium methacrylate.

wide ranges of free energies, particularly that of Vroman,[8-10] has shown that proteins can adsorb on almost any surface and, hence, on contact lens polymeric materials. Protein deposition on contact lenses has been studied extensively both in vivo and in vitro by the analysis of protein deposits,[5,11] by removal of protein deposits,[12] and by conformational changes of contact lens-adsorbed proteins.[13-15] Although the studies have shown that protein deposition on contact lenses has been influenced by many factors—including lens surface chemistry, ionic character, degree of hydration, individual patient tear chemistry, evaporation rate, and design and fit of the lens[5,16,17]—little is known about the extent and mechanisms by which these factors affect protein deposition, in particular the tightly bound layer of protein deposits that could not be removed by proteolytic enzyme lens cleaners.[12] In this study, adsorption of a model protein solution, human serum albumin (HSA), on commercial hydrogel contact lenses of various materials was examined, with emphasis on the extent of irreversible adsorption. Possible driving forces for protein adsorption on contact lenses also were investigated.

MATERIALS AND METHODS

Contact Lenses

The types of commercially available hydrogel contact lenses used in this study were chosen to represent different lens materials of interest. They were unused ACUVUE (Johnson & Johnson, Jacksonville, FL), CIBASOFT (Ciba Vision), and New Vues (Ciba Vision) lenses. Lenses and lens materials are summarized in Table 1.

Other Materials

Human serum albumin (A3782, essentially fatty acid and globulin free, lyophilized, 99%) was obtained from Sigma Chemical (Sydney, Australia). It is a well-characterized protein with a molecular weight of 69,000, and it is shaped like a solid equilateral triangle with sides measuring 80 Å, an average depth of 30 Å,[18] and an isoelectric point of 4.7 to 4.9.[19] Radioactive iodine (^{125}I) was purchased from Australian Nuclear Science and Technology Organisation (Sydney, Australia) in the form of sodium iodide with a specific activity of 80 mCi/ml. All other chemicals were analytical grade and were obtained from Sigma Chemical. Phosphate-buffered saline (PBS) (pH 7.4, ionic strength 0.15 M) was used in the majority of the experiments and consisted of 0.8% NaCl, 0.02% KCl, 0.115% Na_2HPO_4, 0.02% KH_2PO_4, and 0.05% NaN_3 in MilliQ water. The pH 4 buffer solution with ionic strength 0.15 M consisted of 0.276% $Na_2HPO_4 \cdot 12H_2O$ and 0.129% citric acid ($C_6O_7H_8 \cdot H_2O$) in MilliQ water (Millipore, Bedford, MA). The pH 4.8 buffer solution with an ionic strength of 0.2 M consisted of 0.353% $Na_2HPO_4 \cdot 12H_2O$ and 0.107% citric acid ($C_6O_7H_8 \cdot H_2O$) in MilliQ water.

Radio-Iodination of Human Serum Albumin

Human serum albumin was radiolabeled with Na ^{125}I using the chloramine-T method.[20] The unreacted free ^{125}I initially was separated from labeled HSA by chromatography on Sephadex G-25. Just before the adsorption experiment, the labeled HSA (hot) was diluted with unlabeled (cold) HSA solution in certain proportions to achieve a workable specific activity of the mixture of at least 2 cpm/ng, and the protein mixture was dialyzed against PBS for 24 hours at 4°C with three buffer changes. No free ^{125}I was detected in the last dialysis buffer. The activities of hot and cold HSA solutions were measured with a COBRA II Auto-Gamma Counter (Packard Instruments, Meriden, CT). The concentration (C_b) of dialyzed HSA solution was checked from the ultraviolet absorbance at 280 nm (ϵ_{280} = 0.5381 $g^{-1}cm^{-1}$). The specific activity (Sa, cpm/mg) of protein was calculated from equation 1.

$$SA(cpm/mg) = \frac{cpm}{Vol(ml) \times C_b(mg/ml)} \quad (1)$$

where Vol is the volume of solution for counting. The solution of the labeled protein was stored at 4°C for further use within 1 week.

Adsorption, Desorption, and Exchange

Adsorption experiments were carried out at 34°C in polypropylene tubes with 2 cm diameters. Each lens

(total surface area, 3 cm^2) was soaked in 1.5 ml of protein solution with the lens resting on its convex face. The concentration of protein solution for adsorption was 3 mg/ml unless otherwise indicated. After adsorption, the lenses were dipped and rinsed for 15 seconds in PBS, unless otherwise stated, to remove any excess solution adhering to the lenses, and the activities of the "total" adsorbed protein were read. After the initial reading, further desorption of protein molecules from the lenses was determined by soaking the lenses in 40 ml of buffer solution for elution either statically or with machine shaking for various time periods. The value of irreversibly adsorbed protein was obtained after constant radioactivity of the lens surface was reached. Further exchange at 34°C was conducted in cold HSA solution with the same concentration and ionic strength as that for adsorption, unless otherwise indicated. Radioactivity was measured after elution or exchange. Corrections for background and radioactive decay were made. The surface concentration of protein adsorbed on lenses (ng/cm^2) was calculated from equation 2. Samples were measured in triplicate. It should be noted that no

$$ng/cm^2 = \frac{cpm/cm^2}{SA(cpm/ng)} \quad (2)$$

attempt was made to avoid the exposure of lenses to an air–protein solution interface during the change of protein solution to PBS. Some studies do avoid such exposure[21] because of possible denaturation of sensitive proteins at the solution–air and material–air interfaces. However, Feng and Andrade[22] indicated in their study of HSA adsorption on low temperature isotropic carbon that it was not necessary to avoid exposing the HSA-coated material surface to air before elution because there was an insignificant effect on the amount of HSA deposited.

Conductivity Measurement

Each contact lens was first soaked in MilliQ water to wash off buffered saline, a storage medium for commercial lenses, before it was soaked in an excess of 20 ml of 0.1 M HCl solution overnight. Lenses were washed extensively with MilliQ water; then two lenses of the same type were soaked in 10 ml of NaOH solution (0.01 M) for 5 hours. The constant conductivities of the NaOH solution, initial pH 11, were measured with the use of a conductivity meter before and after the protonated lenses were soaked. An estimate of the relative quantities of possible carboxyl charge groups on the lenses was then calculated based on the difference in conductivity of the NaOH solution and the initial concentration of NaOH (pH 11).

Effect of pH on Swelling of Contact Lenses

Contact lenses were rinsed thoroughly with MilliQ water to wash off the buffered saline storage solution and then were soaked in solutions with different pH levels, ranging from 2 to 11. Lens diameters were measured before and after soaking, and the final pH of each solution after soaking was recorded.

RESULTS

Irreversibility of Protein Adsorption

In this study, adsorption of HSA on lens surfaces is assumed. Irreversibility of adsorption can be described from different perspectives. In this study, irreversibility is an operational definition determined both by elutability and by exchangeability. Elutability is defined as how much protein can be washed from a surface by buffer solution, such as PBS, in the absence of added proteins, whereas exchangeability is that proportion of tightly adsorbed protein that can be exchanged or displaced further by proteins in solution. As Figure 1A shows, for all the lenses studied, the remaining HSA on the lenses becomes nearly constant after static elution in PBS for approximately 20 hours. On the other hand, if more energy is applied during elution by machine shaking for various time periods, there is still a layer of HSA remaining on the lens surfaces (Fig. 1B). Furthermore, comparison of the data from Figures 1A and 1C shows that the HSA remaining on the lenses after 24 hours of static elution in PBS is not exchanged or displaced appreciably by the same protein in the exchange solution. Although the amount of HSA remaining on the lenses slightly decreases with time in the exchange protein solution (Fig. 1C), the desorption has a rate similar to that of static elution in PBS after 24 hours (Fig. 1A). The results clearly confirm that effective, irreversible adsorption exists for HSA on all the hydrogel lenses studied.

Adsorption Isotherms

Protein adsorption isotherms of the hydrogel lenses were measured after 24 hours for totally adsorbed HSA (Fig. 2A) and irreversibly adsorbed HSA after 24 hours of static elution in PBS (Fig. 2B). In all cases, the isotherms failed to reach a plateau, even at concentrations as high as 10 mg/ml. On the other hand, the surface concentrations of irreversibly adsorbed HSA are far below the theoretical value of the surface concentration required for a monolayer coverage of HSA in its native state on the lenses (400 to 460 ng/cm^2, based on values from He and Carter[18]). Although the surface concentration of totally adsorbed protein is much greater than that for monolayer coverage of HSA, even at a low solution concentration of 0.5 mg/

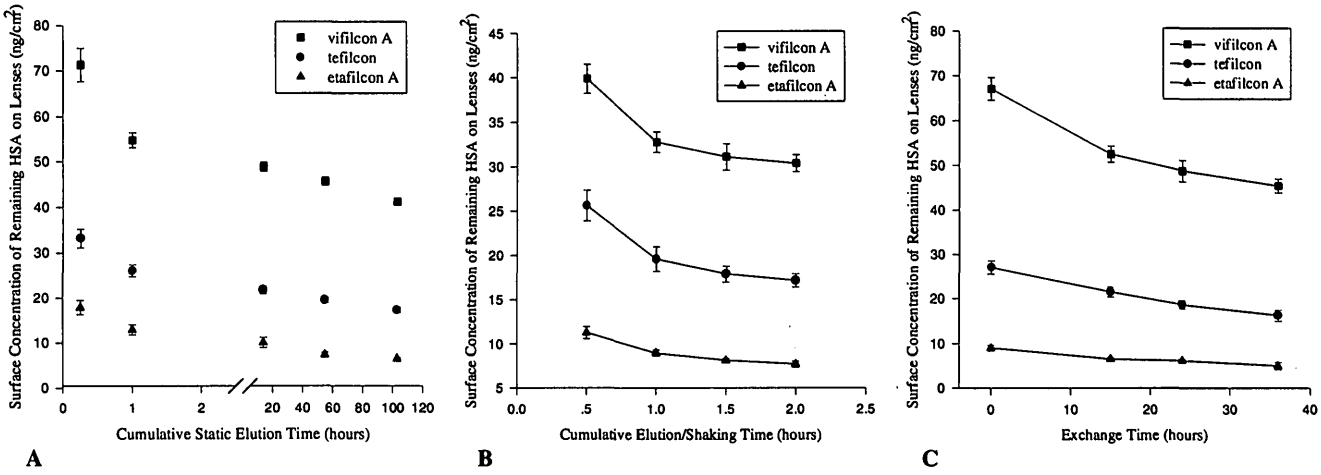

FIGURE 1. Kinetics of human serum albumin (HSA) desorption from hydrogel lenses. Lenses were presoaked in HSA solution (3 mg/ml) for 24 hours followed by (**A**) static elution in phosphate-buffered saline (PBS), (**B**) elution with machine shaking in PBS, and (**C**) 24 hours of static elution in PBS, followed by exchange with unlabeled HSA. 5 mg/ml of HSA solution in PBS was used in **C** for preadsorption and exchange. Error bars show standard deviation (n = 3).

ml, it still increases with the concentration of protein solution. Because the protein solution used for adsorption in this study is a mixture of radioactive (hot) and unlabeled protein (cold), it may be argued that the high value of totally adsorbed protein is caused by the preferential adsorption of the radio-iodinated HSA to the unradio-iodinated HSA. A preferential adsorption test has been conducted to examine this concern. Briefly, the protein mixtures used for adsorption consisted of hot and cold proteins in different ratios, whereas the final concentration was kept constant at 3 mg/ml. The adsorption results (Table 2) show that there is almost no preferential adsorption of the labeled or unlabeled HSA onto the lenses (vifilcon A lenses were chosen for this test).

Adsorption Kinetics

A typical adsorption-versus-time curve for the adsorption of total protein on hydrogel lenses is shown in Figure 3A, where equilibrium was reached rapidly within 15 minutes. It is in agreement with the general observation that protein adsorbs onto soft contact lenses rapidly, usually within the first few minutes. However, Figures 3B and 3C show that the irreversibly adsorbed protein increases with adsorption time. It does not reach equilibrium even after 48 hours of adsorption. In all cases, the irreversible protein adsorbed on the lenses is far below the theoretical value of the monolayer coverage of HSA, whereas the plateau value for total adsorbed HSA is much greater

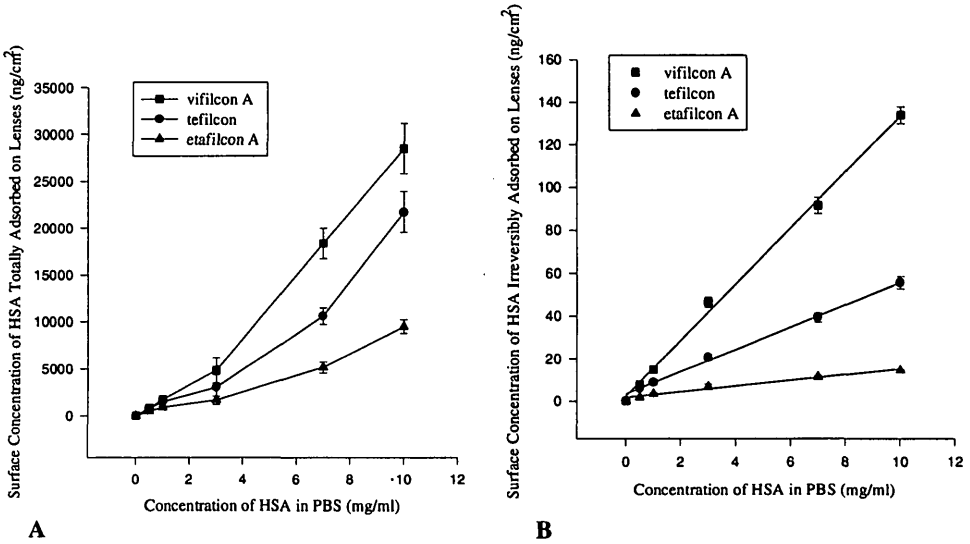

FIGURE 2. Adsorption isotherms for human serum albumin (HSA) on hydrogel lenses. Adsorption time = 24 hours. (**A**) Totally adsorbed HSA. (**B**) Irreversibly adsorbed HSA after 24 hours of static elution in phosphate-buffered saline. Error bars show standard deviation (n = 3).

TABLE 2. Comparison of the Adsorption Properties Between Radioiodinated and Unlabeled HSA on Vifilcon A Lenses*

Ratio† of Hot to Cold Protein in HSA Solution	Total Protein Adsorbed		Irreversible Protein Adsorbed	
	cpm/cm^2	ng/cm^2	cpm/cm^2	ng/cm^2
I	12,390 ± 731	4623 ± 273	35.5 ± 4.4	13.3 ± 1.7
II	17,678 ± 1430	4291 ± 347	56.4 ± 4.5	13.7 ± 1.1
III	33,461 ± 1981	4462 ± 264	111.8 ± 3.3	14.9 ± 0.4

* The final concentration of protein solution was 3 mg/ml. Adsorption time was 1 hour. Elution time in phosphate-buffered saline with machine-shaking was 1 hour (amount adsorbed = average ± standard deviation of triplicate samples).
† I = 54 mg cold HSA in 15 ml PBS + 3 ml hot HSA, specific activity is 2.68 cpm/ng; the concentration of hot protein solution is very low; thus, it can be neglected in calculating the final concentration; II = 54 mg cold HSA in 13 ml PBS + 5 ml hot HSA, specific activity is 4.12 cpm/ng; III = 54 mg cold HSA in 9 ml PBS + 9 ml hot HSA, specific activity is 7.50 cpm/ng.
HSA = human serum albumin.

than the theoretical value. These results suggest a multilayer adsorption process. The first layer is more strongly bound, whereas the other layers are more loosely bound and can be removed by rinsing in buffer solution.

Effect of pH on Protein Adsorption

The effect of pH on the adsorption of protein in buffer solutions, with the ionic strength of 0.15 M for a protein concentration of 5 mg/ml, was examined. Results show that a decrease in pH, from 7.4 to 4.8 and then to 4, results in an increase in the amount of HSA irreversibly adsorbed (Fig. 4). The change in pH does not change the adsorption trends, as observed elsewhere in the present work. Vifilcon A lenses adsorbed the highest level of HSA, whereas the etafilcon A lenses adsorbed the least. The exchange of irreversibly adsorbed HSA at pH 7.4, with HSA in solutions at either pH 7.4 or pH 4, does not show any significant difference on the etafilcon A and vifilcon A lenses (Fig. 5). In fact, the amount of HSA remaining on these two lenses after further exchange has almost the same value as that after further static elution in PBS. However, the irreversibly adsorbed HSA on the tefilcon lenses after adsorption in HSA solution at pH 7.4 is exchanged further in the HSA solution at pH 4 by approximately 50%.

Charge Groups on Hydrogel Lenses

Conductivity results (which give a general trend of measure) show that the amount of carboxyl groups on the hydrogel lenses varies (Table 3). Etafilcon A lenses have the most charge groups, followed by vifilcon A lenses. The charge groups may result from the presence of hydrolyzed sodium methacrylate in the etafilcon A lens materials and hydrolyzed methacrylic acid in the vifilcon A lens materials. A relatively small amount of charge groups was detected on tefilcon

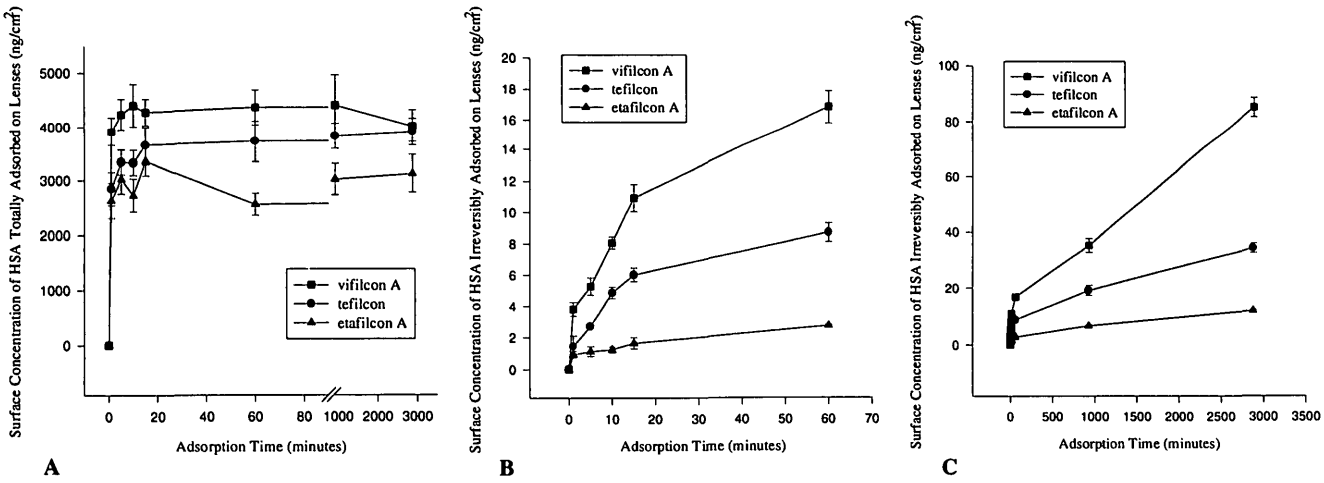

FIGURE 3. Time profile for the adsorption of human serum albumin (HSA) onto hydrogel lenses. (**A**) Totally adsorbed HSA. (**B**) Irreversibly adsorbed HSA for short-term adsorption, 5 to 60 minutes. (**C**) Irreversibly adsorbed HSA for long-term adsorption, 5 minutes to 48 hours. 3 mg/ml of HSA solutions were used for adsorption. Error bars show standard deviation (n = 3).

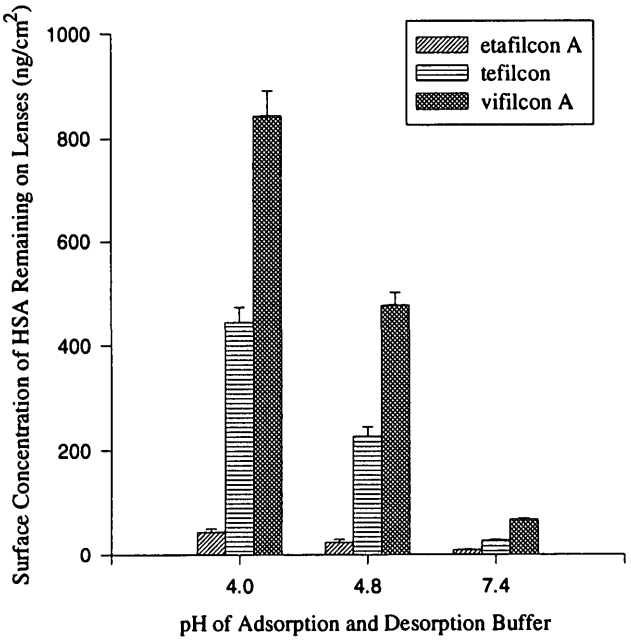

FIGURE 4. Effect of pH on irreversible adsorption of human serum albumin (HSA) onto hydrogel lenses. The lenses were presoaked in HSA solutions with different pH levels: 4, 4.8, and 7.4 for 24 hours, followed by 24 hours of static elution in buffer solutions with corresponding pH levels to the adsorption solution. 5 mg/ml of HSA solutions were used for adsorption. Error bars show standard deviation (n = 3).

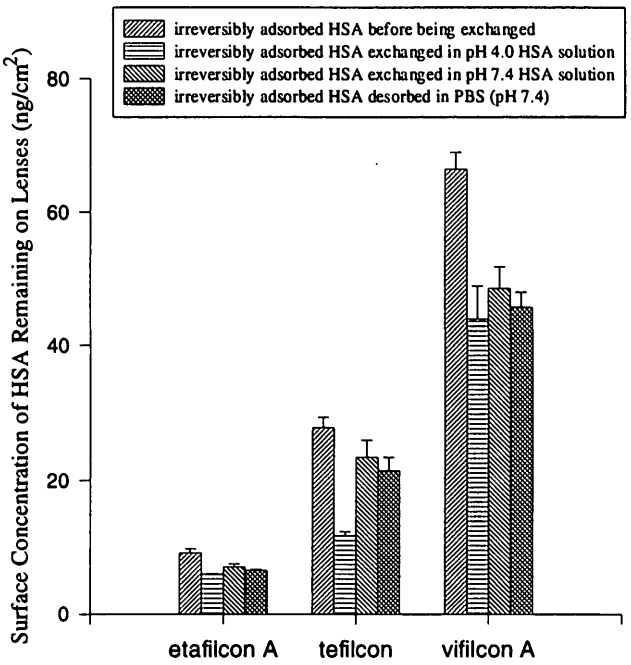

FIGURE 5. Amount of human serum albumin (HSA) remaining on hydrogel lenses after 24 hours of preadsorption in HSA solution in phosphate-buffered saline (PBS; 5 mg/ml, pH 7.4) and further static elution in PBS for 24 hours, followed by exchange or desorption in unlabeled HSA solutions at pH 4 or pH 7.4 (ionic strength, 0.15 M) and in PBS, respectively, for 24 hours. Error bars show standard deviation (n = 3).

lenses, possibly because of the presence of other acid components or contamination by methacrylic acid of this nonionic material. Charge groups on the lenses also can affect lens diameters because the pH of the soaking solution changes, as shown in Figure 6. This result also supports the above observations.

DISCUSSION

Fouling and deposit formation on hydrogel contact lenses by proteins are a major problem in daily and extended wear. They cause the wearer discomfort, limit the lifetime of the lens, and may be responsible for ocular irritation and even damage to the eye. Although much of the protein deposits may be removed by surfactant and enzymatic cleaners, prevention of all protein deposits on lenses has not been successful.[12,23,24] Irreversible adsorption of protein, such as HSA in the current work, may well be related to the initiation of protein deposit formation on hydrogel lenses. An improved understanding of the mechanisms involved should lead to the development of deposit-resistant lens materials and more effective lens cleaning products.

The desorption kinetics (Fig. 1) and adsorption isotherms (Fig. 2) clearly demonstrate that adsorption of HSA on the hydrogel lenses is of a low-affinity type, and the majority of the adsorbed HSA is reversible and can be removed easily by rinsing the lenses in PBS. However, complete desorption of the protein into buffer did not occur after days of static rinsing or with machine shaking, which applies more energy into the desorption system. This supports the general observation that protein desorption can be slow or even nonexistent.[25,26] Moreover, this work finds that although total adsorption of HSA occurs rapidly and reaches a plateau within the first few minutes, irreversible adsorption of HSA also develops simultaneously but at a slow rate (Fig. 3). What leads to such a relatively slow process of irreversible adsorption is not yet known. It is assumed that it may be governed by the kinetics of the conformational change of the adsorbed protein on the lens surfaces.[27] The conformational

TABLE 3. Amount of Carboxyl Groups on Hydrogel Lenses

	COO^- (mol)/g	Relative amount of COO^-
Tefilcon	0.66×10^{-4}	1.0
Vifilcon A	1.61×10^{-4}	2.4
Etafilcon A	2.4×10^{-4}	3.2

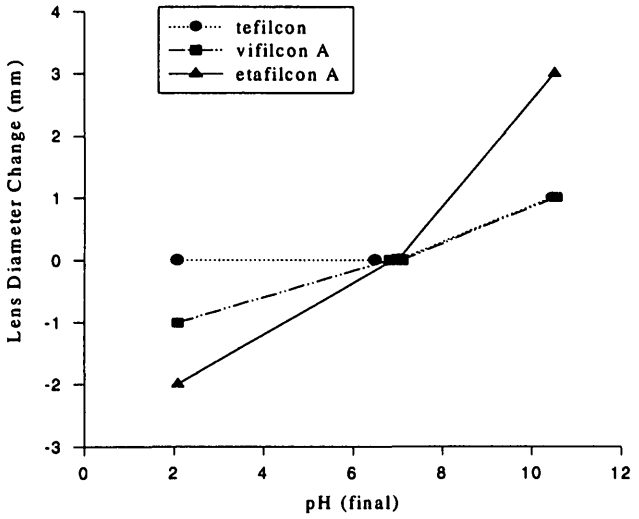

FIGURE 6. Effect of final pH of the solution, after soaking the lenses, on swelling of hydrogel lenses. One sample of each lens was measured in this experiment.

changes in adsorbed human serum albumin on hydrogel lenses were observed, and it was found that no major conformational alteration was detected within a short time of adsorption.[13] However, after longer periods of adsorption, ATR–FTIR spectra of the adsorbed HSA were similar to that observed for heat-denatured HSA. Denaturation of the irreversibly adsorbed HSA may be one of the explanations for incomplete removal of the protein deposits on worn lenses by normal proteolytic enzyme lens cleaners.[12]

It should be emphasized that the extent of irreversible HSA adsorption varies with each lens type (vifilcon A > tefilcon > etafilcon A). Results with such a clear difference show that the impact of the lens materials on protein adsorption is significant. It allows possible mechanisms to be considered, such as electrostatic and hydrophobic interactions, as well as possible interactions of protein to particular monomer units in lens materials. Understanding the above interactions involved in HSA adsorption may lead the way to reducing the irreversible binding of protein to and deposit formation on hydrogel lenses.

It has been observed by many research groups that maximum protein adsorption occurs at the pH closest to its isoelectric point, where protein molecules carry zero net charge and, hence, the electrostatic repulsion between the adsorbed molecules is lowest.[28–30] In this work, the increase in irreversibly adsorbed HSA on the lenses with decreasing pH from 7.4 to 4.8 and 4 is also in line with this general observation (Fig. 4). However, an unexpected result was observed: At pH 4, more adsorption of the now positively charged protein occurred than at the isoelectric point of pH 4.8. The adsorption process, therefore, cannot be explained solely by the net charge of the protein.[30] The carboxyl charge groups present on the hydrogel lenses (those containing methacrylic acid or sodium methacrylate) also may influence the protein–lens interactions. Electrostatic interactions between lens and protein usually are given as one of the reasons for the high adsorption of lysozyme to P(HEMA-co-MA) type hydrogel lenses.[5,21] That the least amount of adsorption of HSA on etafilcon A lenses in buffered solution occurred at pH 7.4, where both protein and lens polymers are negatively charged, also suggests electrostatic repulsion between protein and lenses. However, the relationship between the charge on the lenses and the amount of HSA adsorbed is not monotonic, possibly because the *N*-vinyl pyrrolidone in vifilcon A has a high affinity for HSA. In fact, the irreversibly adsorbed HSA on lenses occurs at all tested pH conditions. Human serum albumin irreversibly adsorbed on etafilcon A and vifilcon A lenses at pH 7.4 cannot be exchanged further, whereas tefilcon lenses do undergo some exchange that cannot be explained. This creates the concern that irreversible adsorption of HSA on hydrogel lenses may be driven by factors other than pure electrostatic interactions that may favor the adsorption.

It is a general observation that hydrophobic materials adsorb more protein than hydrophilic materials.[21,31] Thus, hydrophobic dehydration resulting from the binding of the protein's internal hydrophobic patches to the hydrophobic regions on the tefilcon lenses may account for the higher adsorption of HSA than that on etafilcon A lenses because tefilcon lenses have a low water content of 38%. In the case of hydrogels, however, high water content does not necessarily mean highly wettable surfaces.[32] Hence, whether lens surface hydrophilicity plays an important role in irreversible adsorption of protein warrants further investigation. A series of poly(HEMA)-based hydrogels with controlled numbers of charge groups, specific monomer units commonly present in hydrogel lens materials, and different water contents is being synthesized for further understanding of protein deposit formation on hydrogel lenses at fundamental levels.

Protein adsorption is the overall result of various types of interaction between the different components present in the system,[27] that is, the sorbent surface (lens surface), the protein molecules (HSA), the solvent (water), and any other solutes such as ions present in buffer. An advantage of the in vitro experiments with unworn lenses soaked in a single standardized protein solution is that only the effect of the lens on protein deposition is seen. Comparison of the results from clinical worn lenses (worn by different persons, possibly under different environmental conditions and cleaning procedures) may be made with those obtained from in vitro studies, leading to the development of an in vitro model study that would be useful for the fundamental understanding of protein deposi-

tion on hydrogel lenses. However, careful attention should be paid to the transfer of results obtained from in vitro studies to the living eye. Individual lens wearer-related factors, such as tear quantity, tear evaporation rate, and lid wiping action, also influence protein deposition. In addition, competition among the different proteins in tears may lead to different adsorption processes to those of single protein adsorption in vitro. Combined in vivo and in vitro studies would help in the design of protein deposit-resistant hydrogel lens polymeric materials in terms of water content, ionicity, and specific chemical functional groups.

In aqueous media, hydrogel contact lenses become porous, and, when they are in contact with a protein solution, two phenomena may occur: adsorption of proteins and penetration of proteins—depending on the porosity of the lenses. Lens porosity is governed by many factors, such as lens material, the degree of cross-linking, and the method of manufacture of lenses. For example, the lathe-cut lenses (tefilcon lenses) may have a more open network structure at the surface than the molded lenses (vifilcon A and etafilcon A lenses). The assumption that HSA adsorbs only on the lens surfaces is made from other work in this laboratory. Human serum albumin was found not to penetrate into carboxymethyl poly(hydroxyethyl methacrylate) (CM-PHEMA) hydrogels, even when the water content was as high as 77% (unpublished results, 1996). This was inferred from a comparison of the amount of HSA bound to CM-PHEMA hydrogels using a radiolabel-tracer technique with that using x-ray photoelectron spectroscopy. The three lenses in this study had water contents no higher than 58%. Other studies[21,33] also indicated that no penetration of albumin was detectable in PHEMA hydrogels with water content similar to that of tefilcon lenses (38%). It is not possible to discount the partial entry of HSA into the porous polymer network at the surface of the lens. However, because it appears that penetration into the bulk is not detectable at this stage, the interaction of HSA with the surface has been classified as adsorption only in this study.

In summary, HSA adsorption onto hydrogel contact lenses leads to multilayer adsorption by two processes occurring simultaneously with very different adsorption rates. Most adsorbed HSA is reversible and can be desorbed from the lens surfaces easily. Irreversibly adsorbed HSA is confirmed clearly on all the lenses studied, although its value is low. Creation of irreversibly bound HSA on lenses is a relatively slow process that may be governed by the kinetics of protein denaturation. Lens materials have a great impact on the irreversible adsorption of HSA. The extent of irreversibly adsorbed HSA on the three hydrogel lenses is in the order of vifilcon A > tefilcon > etafilcon A. Electrostatic interactions may not play a major role, but some other factors, such as hydrophobic dehydration, and possible interactions of HSA with particular monomer units, such as N-vinyl pyrrolidone in vifilcon A, may favor irreversible adsorption of HSA.

Key Words

human serum albumin, hydrogel contact lens, irreversible adsorption, lens protein deposits

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